

N93-18714

EVIDENCE FOR A MASSIVE STELLAR BLACK HOLE IN
X-RAY NOVA MUSCAE

Wan Chen¹ and Neil Gehrels

NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771

and

F.H. Cheng

*Space Telescope Science Institute, Baltimore, Maryland 21218, and
Center for Astrophysics, University of Science and Technology of China, Hefei, China*

Submitted to *The Astrophysical Journal, Letters*

¹Universities Space Research Association

Abstract

We present evidence that the X-ray Nova Muscae system contains a massive, $> 10M_{\odot}$, black hole. The recently measured photometric binary mass function of Remillard, McClintock, & Bailyn (1992) gives the black hole mass for this system as a function of orbital inclination angle. From the spectral redshift and width of the positron annihilation γ -ray line observed by GRANAT/SIGMA, we find the accretion disk inclination angle to be $22^{\circ} \pm 18^{\circ}$. Assuming the accretion disk lies in the orbital plane of the system, the black hole mass is found to have a lower limit of $14 M_{\odot}$ although statistics are poor. This is supported by spectral modeling of combined optical/UV/x-ray/ γ -ray data and by a new Nova Muscae distance limit we derive of > 3 kpc. The large mass for this black hole and the high binary mass ratio it implies (> 20) raise a serious challenge to theoretical models of the formation and evolution of massive binaries. The γ -ray line technique introduced here can give tight constraints on orbital parameters when high-sensitivity line measurements are made by such missions as *GRO*.

1 INTRODUCTION

The X-ray Nova Muscae 1991 (GRS1121-68=GS1124-683, hereafter XN Mus) was discovered on 9 January 1991 by the all-sky monitors onboard both the GRANAT and Ginga satellites (Lund & Brandt 1991; Makino 1991), and was subsequently observed by all the X-ray and γ -ray instruments in orbit: by ART-P and SIGMA on GRANAT in 3-1300 keV (Grebenev, Sunyaev, & Pavlinsky 1991; Gilfanov et al. 1991), by GINGA in 1-37 keV (Tanaka, Makino, & Dotani 1991), and by ROSAT in 0.4-2.3 keV (Greiner et al. 1991). The early optical and X-ray light curve and spectral behavior of XN Mus are remarkably similar to that of the black hole system A0620-00 (=V616 Mon; Tanaka, Makino, & Dotani 1991), which suggests that XN Mus also contains a black hole. Observations at ESO (Della Valle, Jarvis, & West 1991a,b) have identified the optical counterpart of XN Mus both before and

after the outburst as a K-M dwarf orbiting a compact object, probably a black hole (Della Valle, Jarvis, & West 1991b), located at an estimated distance of 1.4 kpc. The binary period of the system was later found to be 10.5 hours (Bailyn 1992). By modeling the HST/FOS observation of XN Mus together with the spectra from ART-P, NTT (Della Valle, Jarvis, & West 1991a) and IUE (Shrader & Gonzales-Riestra 1991), Cheng et al. (1992) found that the broadband spectrum and its evolution can be well fitted by a standard black-body thin accretion disk model (Czerny, Czerny, & Grindlay 1986). The *minimum* compact object mass in this analysis is found to be $12.5 M_{\odot}$ using the observed orbital period and a distance of ~ 5 kpc.

Yet the ultimate proof of the presence of a black hole in XN Mus relies on the dynamic evidence of the mass of the compact object. Optical photometry and spectroscopy of XN Mus in quiescence obtained recently at CTIO (Remillard, McClintock, & Bailyn 1992) give a mass function,

$$f \equiv \frac{(M \sin i)^3}{(M + M_c)^2} = 3.07 \pm 0.4 M_{\odot}, \quad (1)$$

where M and M_c are the masses of the primary and companion, and i is the orbital inclination angle of the system ($i = 0$ is face-on). For reasonable values of the mass range for the K0V-K4V dwarf companion ($0.3-0.7 M_{\odot}$) and the orbital inclination angle ($i < 80^{\circ}$ for lack of optical and X-ray eclipses), the compact primary has a mass $M > 3.75 M_{\odot}$ and is therefore very likely a black hole. To further pin down the primary mass, one needs to know more about the orbital inclination angle of the system which, unlike the partially eclipsing binary A0620-00 (Haswell 1991), cannot be obtained from optical photometry or spectroscopy for XN Mus. In this letter we show that such geometric information can be inferred from the central energy and width of a γ -ray emission line from XN Mus.

2 MODEL

Twelve days after the hard X-ray outburst, a most remarkable transient emission feature was observed in the high energy spectrum of XN Mus by SIGMA (Sunyaev et al. 1992; Goldwurm et al. 1992). The line radiation was seen only for a few hours, with central energy ~ 480 keV and a FWHM ~ 60 keV. The most natural interpretation is that it is a positron annihilation line (rest-frame energy $E_0 = 511$ keV) radiated from the vicinity of a compact object and so is gravitationally redshifted by about 6%. An emission line of energy E_0 radiated at a distance r from the compact object is observed to be redshifted to $E = E_0 - \Delta E$ where $\Delta E/E_0 = 1 - (1 - r_s/r)^{1/2}$ and $r_s = 2GM/c^2$ is the Schwartzchild radius. For XN Mus, the reported annihilation radiation is centered at $E = 481 \pm 22$ keV from Goldwurm et al. (1992) and at 476 ± 15 keV from Sunyaev et al. (1992). If we adopt the mean value, 479 ± 13 keV, the redshift is then $z = \Delta E/E = 0.068 \pm 0.030$ and the annihilation radius $r = 8.2 \pm 3.5 r_s$.

There is other observational evidence that the annihilation photons are produced near the black hole. First, there is a narrow emission feature ~ 200 keV that appeared in the high energy spectrum of XN Mus at the same time as the annihilation feature (Sunyaev et al. 1992; Goldwurm et al. 1992). This can be attributed to annihilation photons escaping from the inner region of the accretion disk and then being Compton reflected by the outer part of the disk (Lingenfelter & Hua 1991). Second, no three-photon positronium continuum is found in the annihilation spectrum of XN Mus (Grebenev, Sunyaev, & Pavlinsky 1991), suggesting that the annihilation site is hotter than 10^5 K (Bussard, Ramaty, & Drachman 1979) or denser than 10^{14} cm $^{-3}$ (Crannel et al. 1976) and is therefore near the black hole.

One may argue that the line redshift is due to the Doppler effect of a jet of annihilating $e^+ - e^-$ pairs emanating from the system, but we believe this is unlikely. Accretion systems usually have, if any, *two* jets in opposite directions, so we should see both blueshifted and

redshifted lines. However, in XN Mus only a redshifted component was seen. All the physical mechanisms for hiding one jet (e.g., Lorentz boosting or disk shadowing) would allow the observer preferentially to see the one which is *blueshifted* rather than the redshifted one. So the line redshift is not due to the Doppler effect unless the system produces only a single jet which happens to be moving away from us and is not obscured by the accretion disk in the system. We also draw the reader's attention to similar *transient* and *redshifted* annihilation radiation observed from the Galactic Center γ -ray source 1E1740.7-2942 by SIGMA (Bouchet et al. 1991) and from a hard X-ray source observed by HEAO A-4 instrument (Briggs 1991). For comparison, we plot the original spectra of the three sources together in Fig. 1. The redshifts in all three detected annihilation features are quite similar which favors their gravitational origin.

Is the annihilation site more likely in a pair cloud surrounding the black hole or in the inner region of the accretion disk? From a theoretical point of view, the accretion disk is undoubtedly the favorite choice. Near the black hole, high energy $e^+ - e^-$ pairs are thought to be created via $\gamma - \gamma$ collisions to form a pair cloud (e.g., Liang 1991) and subsequently blown away by radiation pressure (Sunyaev et al. 1992). In the inner region of the accretion disk with densities of order $10^{18} - 10^{20} \text{ cm}^{-3}$ (Czerny, Czerny, & Grindlay 1986), the high energy positrons intercepted by the disk slow down and annihilate within a few r_s . Such an idea has recently been proposed by Ramaty et al. (1992) to explain the annihilation feature observed in 1E1740.7-2942. There is actually direct observational evidence that the annihilation in XN Mus takes place in an accretion disk. Gilfanov et al. (1991) report that the line shape may be more complicated than a simple Gaussian profile if the data are binned in the narrowest ($\Delta E \sim 15 - 20 \text{ keV}$) detector channels (see the inset graph in Fig. 1(a)). The line shape can be better described by *two narrow components* than by a single broad line. A double-peaked line profile is exactly what one would expect from the Doppler effect of Keplerian motion in an accretion disk (Chen & Halpern 1989; Bhattacharya & Gehrels

1991). Although the relatively poor statistics in the line does not allow a firm conclusion, we regard this as an important clue.

The width of an emission line from an accretion disk is affected by both thermal broadening and disk rotation. If in XN Mus the maximum disk temperature is ~ 0.8 keV from ROSAT spectral fitting (Greiner et al. 1991), the thermal contribution to the line width is ~ 30 keV. Since the line radiation comes $\leq 10r_s$ from the black hole, the large Keplerian velocity of the disk rotation may broaden the line to as wide as > 100 keV. However, the observed line width of the annihilation feature is much less, about 60 keV (see below). If one believes the gravitational origin of the line redshift, the only way to reconcile the discrepancy is to assume the accretion disk in XN Mus has a small inclination angle to our line of sight. Thus, the observed narrow annihilation line width of XN Mus provides a rare and unique opportunity for us to estimate the orbital inclination angle of the system (and so the mass of the black hole!) since the disk usually lies in the orbital plane.

The reported annihilation line has a FWHM = 58 ± 34 keV from Sunyaev et al. (1992). Using the instrument spectral resolution at 500 keV of about 9% (Paul et al. 1991), one derives an intrinsic line width of $\Delta E = 37 \pm 43$ keV, which differs somewhat from that reported by Goldwurm et al. (1992), 54 ± 54 keV. The rotational line broadening, $(\Delta E)_K$, is related to the total intrinsic line width, ΔE , and the disk inclination angle by $\Delta E = [(\Delta E)_T^2 + (\Delta E)_K^2]^{1/2}$ and $(\Delta E)_K/E \sim v/c \cdot \sin i$, where $(\Delta E)_T = 37$ keV $(T/\text{keV})^{1/2}$ is the thermal broadening, E is the redshifted line center energy, and $v/c = (GM/c^2r)^{1/2} = (r_s/2r)^{1/2}$ is the Keplerian velocity at radius r . This gives $\sin i = (2r/r_s)^{1/2}(\Delta E)_K/E$, which can be used with eq. 1 to calculate the mass of the compact primary, M , assuming a companion mass $M_c = 0.5 \pm 0.2M_\odot$. The results are listed in Table 1. Because of the large uncertainties in the line widths, we can not use the first-order error propagation method. Instead, we assume a Gaussian error distribution in the line width and calculate the mean and standard deviation of the derived parameters using exact formulae. Since both reported

line widths allow arbitrarily small inclination angle, no upper limit on the black hole mass can be derived. The lower limits on the black hole mass listed in Table 1 are calculated from the largest inclination angle $\sin i + \Delta \sin i$.

Indirect evidence of a large black hole mass in XN Mus can also be obtained by modeling the broad band optical-to-hard-X-ray spectrum. Using a standard thin accretion disk model Cheng et al. (1992) found a lower limit for the mass of the black hole of $12.5 M_{\odot}$. However, we have included the ROSAT soft X-ray data and find that the simple thin blackbody disk model is no longer valid. Although the ROSAT spectrum by itself can be fitted by a thin disk model (Greiner et al. 1991), the observed soft X-ray flux is almost an order of magnitude less than the extrapolation from the optical and UV data. On the other hand, the relatively large absorption column also allows the ROSAT spectrum to be equally well fitted by a power law (Greiner et al. 1991). In this case, if we require that the extrapolation of the UV disk emission to soft X-rays does not exceed the power law flux, we get a lower limit on the black hole mass of $\sim 30 M_{\odot}$. Further detailed modeling is underway.

3 DISCUSSION

Under the assumptions that (1) the annihilation line centroid redshift is purely gravitational and (2) the line width is caused by the combined effect of temperature broadening and accretion disk rotation, we are able to estimate the orbital inclination angle of the XN Mus system and then to constrain the black hole mass. The major uncertainties in our results are due to the uncertainties in the reported line widths. Because of the measured narrow line width, the inclination angles are small and we conclude that the black hole mass is probably $> 10 M_{\odot}$. The mass ratio in this binary system reaches a new record, > 20 (assuming the companion mass of $0.5 M_{\odot}$). This is the first time a γ -ray line has ever been used to determine the geometry of an accretion disk system, though the poor photon statistics in

this data set introduces large uncertainties in the deduced black hole mass. This technique, however, can certainly be used in future, more sensitive γ -ray line observations such as those performed by the *Compton Gamma Ray Observatory* to achieve much better precision.

An interesting complication to our interpretation is Compton scattering (Leventhal 1992). As the annihilation photons make their way out of the accretion disk, they can be Compton back-scattered to produce the 200 keV feature observed in the XN Mus spectrum. The forward-scattered photons will form a continuum (similar to that caused by the positronium three-photon annihilation) at energies below 511 keV (Lingenfelter & Hua 1991). When this continuum plus line are convolved with the finite detector energy resolution, the measured line can be redshifted and broadened (Leventhal 1973). However, the lack of positronium continuum below the line and the low value (< 0.3) of the observed line flux ratio between the 200 keV and 480 keV features indicate a small Compton optical depth (Lingenfelter & Hua 1991) and thereby a small contribution to the annihilation line profile.

The distance to XN Mus is not well determined. Della Valle, Jarvis, & West (1991a) give an estimate of 1.4 kpc using optical data. Grebenev, Sunyaev, & Pavlinsky (1991) confine it within $0.5 < D < 5$ kpc from ART-P data. Cheng et al. (1992) derive a large value of 8 kpc from the pre-nova companion brightness. The reported column density towards XN Mus from ROSAT observations (Greiner et al. 1991) is $1.45 \times 10^{21} \text{ cm}^{-2}$ which is consistent with the color excess $E(B - V) = 0.29$ measured with IUE and HST (Cheng et al. 1992). Using the empirical relationship between column density, galactic latitude and the distance above the galactic plane (Diplas 1992), we find that XN Mus ($b^{\text{II}} = -7.1^\circ$) has reached the *maximum* absorption for that latitude and is at least 300-400 pc above the galactic plane. This implies a *minimum* distance of 3 kpc and is fully consistent with 8 kpc. A nearby star, GS Mus, at the same galactic latitude and having similar column density has a distance of 5.2 kpc. The combined X-ray luminosity from both ROSAT and ART-P taken about two weeks after the hard X-ray continuum outburst is $\sim 1.3 \times 10^{38} \text{ ergs s}^{-1} (D/3\text{kpc})^2$. If we

require that the total X-ray luminosity at that time does not exceed 20% of the Eddington limit, as indicated by its hard X-ray luminosity evolution (Grebenev, Sunyaev, & Pavlinsky 1991) and ROSAT spectral fitting (Greiner et al. 1991), the black hole mass is found to be $M \geq 4.5M_{\odot}(D/3\text{kpc})^2$. If the distance is 8 kpc as suggested by Cheng et al. (1992), the lower limit is then $32M_{\odot}$.

The large mass of the black hole in XN Mus conjectured in this paper may be pushing the current theoretical tolerance on the mass of a stellar-sized black hole and the mass ratio in a binary system. In the current massive star evolution model, the iron core mass at the end of the evolutionary track determines whether the final product becomes a black hole or not. If the core is greater than about $1.4M_{\odot}$, it will collapse into a black hole rather than form a neutron star. When this happens, the lack of a hard shell surface to bounce back the collapsing mass will prevent a massive supernova explosion and the whole remnant star can fall into the black hole in a more or less spherical fashion. Thus, one might expect that massive black holes are common since the main sequence mass spectrum extends to above $100M_{\odot}$. The problem is that most theoretical models predict all massive stars of solar abundance go through a Wolf-Rayet phase during which mass loss is severe. The mass left at the end of the evolution becomes very small ($< 10M_{\odot}$) for almost the entire mass spectrum. The more massive a star is, the more severe its mass loss. So the most massive stars may not necessarily produce the most massive black holes. One way out of this dilemma is to let the star collapse before it enters the Wolf-Rayet stage, e.g. in the blue supergiant phase as in the case of SN 1987A. But how this is done for stars of solar abundance is still an open question.

Another alternative is to produce a massive black hole through binary interaction. This is also directly related to our second problem of producing a close binary system of extreme mass ratio. A particularly interesting model (Eggleton & Verbunt 1986) has been proposed specifically for the black hole system A0620-00 in which a triple star system goes through

two common envelope phases to form a black hole and a low mass close companion. In this scenario, the progenitors are two massive stars in a close orbit joined by a late dwarf at large distance. The massive binary first evolves into a normal high mass X-ray binary, and the compact object (either a black hole or a neutron star) spirals into and merges with the core of its companion when the latter evolves into a supergiant. When the envelope of the companion reaches the late-dwarf orbit, the latter spirals in to form a low mass close binary. Since the compact object directly accretes matter from its massive companion, it can become a black hole with much more mass than single star evolution would allow. This picture may be plausible if one considers that triple stars occur in as many as 15-20% of the stellar systems.

We are grateful to Jim Pringle and Mario Livio for helpful conversations, and to Michael Briggs for permission to use a figure from his thesis and for useful conversations. We thank Athanaasios Diplas for providing the extinction curve and especially Marvin Leventhal for a critical reading of the manuscript.

TABLE 1 Annihilation line parameters and derived black hole mass

Parameters	Groups		
	Goldwurm et al.	Sunyaev et al.	Mean
Line center E (keV)	481 ± 22	476 ± 15	479 ± 13
Center redshift z	0.062 ± 0.049	0.074 ± 0.034	0.068 ± 0.030
Annihilation radius (r_s)	8.8 ± 6.2	7.6 ± 3.1	8.2 ± 3.5
Intrinsic FWHM (keV)	54 ± 54	39 ± 37^a	47 ± 33
Rotational FWHM ^b (keV)	46 ± 50	31 ± 36	38 ± 31
$\sin i$	0.38 ± 0.41	0.25 ± 0.29	0.32 ± 0.25
Inclination angle i	$27^\circ \pm 31^\circ$	$16^\circ \pm 20^\circ$	$22^\circ \pm 18^\circ$
Black hole mass (M_\odot)			
Lower limit (1σ)	7.2	20	14

^a Derived from the observed FWHM by removing the instrumental width.

^b After removing thermal broadening from the intrinsic width.

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FIGURE CAPTIONS

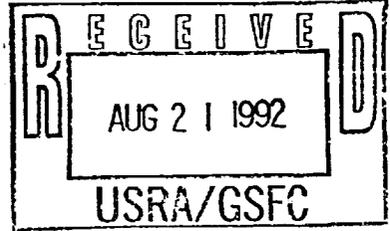
Fig. 1 The photon spectra of the three known hard X-ray sources that have shown positron annihilation features. (a) X-ray Nova Muscae 1991 (from Goldwurm et al. 1992); (b) 1E1740.7-2942 (from Bouchet et al. 1991); and (c) HEAO A-4 source (from Briggs 1991). The *solid* lines are the best fit continuum plus a Gaussian annihilation profile. A *dashed* vertical line is drawn at 511 keV as a reference to show the redshift of the lines. The annihilation lines in both (b) and (c) are very broad which is consistent with disk broadening at a large viewing angle (edge-on systems). The emission feature in XN Mus is considerably narrower, indicating a face-on system (see text). In panel (a), there is also a possible Compton reflection feature near 200 keV. The inset graph shows the SIGMA count spectrum of the annihilation feature after removing the power-law continuum (adopted from Gilfanov et al. 1991).

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660-044

UNIVERSITIES SPACE RESEARCH ASSOCIATION
GODDARD VISITING SCIENTIST PROGRAM

EMPLOYEE SUMMARY OF ACCOMPLISHMENTS
(for the year ending 9/30/92)



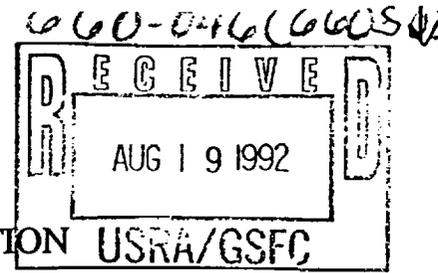
Employee Name: Helmut Seifert Task Number: 660-044

General Description of Your Research Activities: (Include a Paragraph on each Activity).

As instrument scientist I have been working on various aspects of the instrument development for The Transient Gamma-Ray Spectrometer (TGRS) which has been chosen, under the Global Geospace Science (GGS) mission, to fly on the WIND spacecraft due to be launched in fall of 1993, and is designed to perform high resolution studies of gamma-ray burst spectra.

I have been leading and supervising the design, development, implementation, and testing of a data analysis package for TGRS, as well as the completion of the Ground Support Equipment (GSE) software. This included writing requirements/specifications documents, and the development and testing of the algorithms which are used by our software. My other responsibilities in the laboratory are to lead the testing of the experiment analog/digital electronics, and the flight software.

I am actively involved in the planning and preparations for the various tests during the integration phase of TGRS. I am taking a leading part in carrying out these tests, as well as all the necessary calibrations of the instrument. After the launch of TGRS, I will participate in the scientific analysis and interpretation of the experimental data.



UNIVERSITIES SPACE RESEARCH ASSOCIATION
GODDARD VISITING SCIENCE PROGRAM

EMPLOYEE SUMMARY OF ACCOMPLISHMENTS
(for the year ending 9/30/92)

Employee Name: James Lochner

Task Number: 5000-646

General Description of Activities:

Summary: I hired on with USRA in late October 1991, having just completed a post-doctoral position with the Space Astronomy and Astrophysics group at Los Alamos National Laboratory. In the past year my programmatic USRA activities have been with the High Energy Astrophysics Science Archive Research Center (HEASARC), and with the X-ray Timing Explorer Guest Observer Facility (XTE GOF). My major programmatic accomplishments include: 1) transferring the *Vela 5B* All Sky Monitor data from Los Alamos to the HEASARC; 2) developing a plan for user access to these data; 3) transferring the *Ariel 5* All Sky Monitor data from the GSFC IBM 3081 to the HEASARC; and; 4) developing requirements and implementation plans for the XTE GOF. Research activities have centered on utilizing the *Vela 5B* data in the study of the soft x-ray transient 4U 1608, and in monitoring the previous history of new sources and new reports of long term periodicities.

Vela 5B

The *Vela 5B* All Sky Monitor data base offers a unique 10 year history of the x-ray sky from 1969 - 1979. The inclusion of this data base into the HEASARC represents a major contribution in its efforts to assemble and make available data from past missions. While at Los Alamos, I utilized this data base in my research of long term variability of galactic x-ray sources. During my first two months with USRA, I remained at Los Alamos to carry out the transfer of the data base to the HEASARC. This was accomplished through coordinating the data transfer with system personnel at Los Alamos and at Goddard's National Space Science Data Center Data Archive and Distribution Service (NDADS). By Dec 31, 1991 the 6 Gbyte database had been transferred via computer networks to optical platter on the NDADS system and became part of the newly created Automatic Retrieval Mail System. The *Vela 5B* data were the first non-GSFC resident data to be made a part of that system, and demonstrated the ease with which such a transfer is possible.

While at Los Alamos, I also developed a plan for user access to the *Vela* data. The plan includes producing products in the form of light curves for sources of general interest. Because of the nature of the *Vela 5B* data, these light curves are obtained in one of two ways: either a simple

extraction from the data base for isolated x-ray sources, or a fitting of an intensity map for more crowded regions of the sky. The plan lists approximately 70 x-ray sources, divided into those two categories. The plan includes criteria for acceptance of the data from the sky fits, and algorithms for implementing these criteria were initiated while I was at Los Alamos. The plan also includes a means for users to obtain light curves for sources not part of the pre-selected list.

Once at Goddard, I set up an environment on the HEASARC computers in which to gain access to the data on the NDADS platters. I implemented algorithms used at Los Alamos for constructing the isolated source light curves and for fitting the sky maps. Such an environment and such computer code not only facilitate the creation of the data products, but will also ultimately be the basis for user access to new sources.

In April, shifted the bulk of my time to the XTE-GOF (see below), handing over the *Vela 5B* project to Dr. Laura Whitlock (USRA). Since then, I have collaborated with Dr. Whitlock on policy issues and pragmatics concerning the development of this data base in the HEASARC.

Ariel 5 All Sky Monitor

The All Sky Monitor aboard the *Ariel 5* satellite adds to the *Vela 5B* history of the x-ray sky from 1974 - 1980. These data have long been resident in the tape library of the GSFC IBM 3081, but with changes in the IBM system these data were threatened with extinction. I worked with Katherine Rhode (STX-HEASARC) to rescue these data and transfer them to the HEASARC system. Because the data were already in the form of light curves, we needed only to identify the sources of interest, matching this list to that for the *Vela 5B* data. Once transferred to the HEASARC system, we defined FITS format definitions for these light curves to conform to the format for data products in the HEASARC system. The conversion of the files to these formats was taking place at fiscal year end.

The *Ariel 5* effort is another task taken over by Dr. Whitlock, with myself acting in consultation.

XTE Guest Observer Facility

In April, I shifted my programmatic efforts to the XTE Guest Observer Facility. This new facility within the XTE Science Operations Center (SOC) was created to separate out functions serving guest observers from the day-to-day operations of the satellite. The Office of Guest Investigator Programs (OGIP) in the Lab for High Energy Astrophysics oversees the operation of the GOF (as well as of the HEASARC).

Upon joining the GOF, I took the lead in writing a document describing the GOF's responsibilities and requirements. This was done through a series of meetings with the other GOF personnel, the Science Operations Facility (SOF) personnel and the manager of the SOC. We successfully identified the GOF requirements, and its interfaces to the SOF, the HEASARC and to NASA Headquarters. I also participated in the development of the SOC software build plan, which describes a schedule for implementing the SOC requirements, including those of the GOF. This work has necessitated discussions with the software personnel for the three instrument teams

("PIs") which make up the XTE satellite. I have also participated in the group effort to design the software system using an object-oriented environment.

I have also played an active role in a number of important XTE meetings. At the XTE Science Working Group meeting June 23-25, I presented a summary of the GOF requirements. I organized and conducted the second of the SOC-PI Software Interface meetings Aug 13-14, and gave a presentation of the implementation plan to the SOC Preliminary Design Review Sept. 3-4.

Non-programmatic Research Activities

4U 1608-52: The *Vela 5B* data augments the outburst history of the soft x-ray transient 4U1608-52. I and Dr. Diane Roussel-Dupré (Los Alamos) have been studying the history of the transient during the time observed by the *Vela 5B* satellite. These data present four previously unknown transient outbursts in the early 1970's. The history of the outbursts reveals a possibly 20 day underlying cycle, but one in which outbursts do not always occur on the cycle. Further, one outburst in 1970 is particularly peculiar, since it is symmetric in its time profile rather than having a rapid rise and exponential decay. This outburst also reveals the presence of a 4.14 day orbital period, and another 20 day period presumably due to precession of an accretion disk. Both periods are new results for this system, and we interpret them in terms of a disk outburst model. This work is being submitted for publication as this review period comes to a close.

Miscellaneous: I continue to use the *Vela 5B* data to investigate reports of long term periods x-ray sources, and to look for previous outbursts of new transients. Among such work this past year, I examined LMC X-3 for a ~ 190 d period (Cowley, A. P. *et al*, 1991, *Ap.J.*, 381, 526). Because of limitations in the data, I obtained a null result. In addition, I looked into the past history of some of the transients seen by the Ginga satellite. I also renewed a project to examine the evolution of the binary light curve of Circinus X-1, in an attempt to understand the orbital properties of the system.

Recognition of Work:

Recent Science Citations (1989 - 1991) show 6 references to my thesis work, published in 1989, *ApJ*, 337, 823.

Papers Published or Accepted for Publication:

"Long-Term Variability in Low Mass X-ray Binaries: A Study using Data from *Vela 5B*," Smale, A. P. (USRA-GSFC) and Lochner, J. C. (USRA-GSFC) 1992, *ApJ*, 395, 582. [abstract enclosed]

Papers Submitted but not yet Accepted for Publication:

"Recurrence times and Periodicities in 4U 1608-52 as Observed by *Vela 5B*," Lochner, J. C. (USRA-GSFC) & Roussel-Dupré, D. (Los Alamos), Submitted to ApJ. Sept. 15, 1992.

Papers Presented at Scientific Meetings:

Invited Papers

"Strange Attractors and You," Lochner, J. C., presented at the 1992 Aspen Winter Physics Conference on Astrophysics: "X-ray and Gamma Ray Signatures of Black Holes vs. Neutron Stars", Jan 19 - 25, 1992

Contributed Papers

"Properties of Multiple Event Gamma Ray Bursts", Lochner, J. C., Proc. 1991 Huntsville Gamma Ray Burst Workshop, eds. W.C. Paciesas and G.J. Fishman (AIP: New York), 1992, in press.

Colloquia, Seminars, and Special Lectures

"Analyzing Light Curves for Chaos", Aug 31, 1992, to the LHEA Noontime Gamma-Ray Lunch

Community Service:

I am a member and Vice President for Education of the Triple Crown Toastmasters Club in Bowie Maryland. I often use opportunities in the club to promote a general understanding of science and science issues.

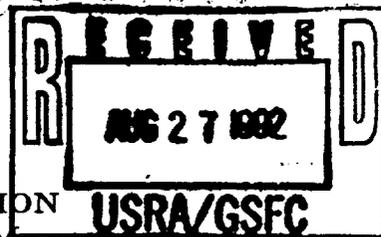
University Collaborations:

- None -

Other Collaborative Activities:

Under Research Activities, I have discussed my collaboration with Dr. D. Roussel-Dupré at Los Alamos National Lab.

The work done on LMC X-3 was done in collaborations with Dr. Tomaso Belloni of the Max Plank Institut in Germany



UNIVERSITIES SPACE RESEARCH ASSOCIATION
GODDARD VISITING SCIENTIST PROGRAM

EMPLOYEE SUMMARY OF ACCOMPLISHMENTS
(for the year ending 9/30/92)

Employee Name: Ivan HUBENY

Task Number: 5000-807

General Description of Your research Activities:

1. *Stellar atmospheres*

- Basic theory of stellar atmospheres: During this period, when new observations of hot stars taken by Hubble Space Telescope became available it became clear that these high signal-to-noise and high-resolution observations have to be interpreted using more sophisticated model stellar atmospheres than those constructed so far. The most important task is to incorporate the effect of thousands to millions of spectral lines, without assuming local thermodynamic equilibrium (LTE), to model atmospheres - the so called non-LTE line blanketing. I have therefore concentrated, mostly in collaboration with Dr. T. Lanz (NRC), on developing the methodology for treating this difficult problem. We have indeed succeeded in developing several new, sophisticated methods which make calculations of non-LTE line blanketed model possible. One such method is the so-called accelerated complete linearization (Ref. 4), the other is a hybrid method between the Accelerated Lambda Iteration (ALI) methods (reviewed in Ref. 3), and complete linearization. The method and the first results are briefly described in Ref. 6, but several other, more detailed, papers are currently in preparation. Generally speaking, the first results look very promising, indicating that the new methods represents a real breakthrough in the field. - etc
- Collaboration with the GHRS group (Drs. S. Heap, B. Altner): A work has continued on interpreting individual hot stars observed by HST (the hot subdwarf BD+75 325 - some results are presented in Ref. 10; the analysis is expected to be finished later this fall), and by other instruments (IUE, optical) - the central star of NGC 6826 (Ref. 11). -
- I have worked with Dr. W. Schmutz (ETH Zurich, Switzerland), during his visit to GSFC this spring, on combining his stellar wind computer program with my synthetic spectrum program with the aim to develop a general spectrum synthesis program for spherical, expanding stars. The work still continues.
- I have worked with researchers from Space Telescope Science Institute (groups of Drs. K. Long and K. Horne) on model atmospheres for solar-composition white dwarfs which are found in some cataclysmic variable systems, observed by Hopkins Ultraviolet Telescope and Hubble Space Telescope (Refs. 5 and 8). - etc
- Dr. D. Mihalas, the leading world authority in the field of stellar atmospheres, has invited me to write with him the third edition of his famous textbook-monograph "Stellar Atmospheres". The second edition was published in 1978, and in between an enormous progress in the field was achieved. During my stay in Boulder in August, we have already started actual work, and prepared a detailed outline of a completely changed book, taking into account all recent developments. - etc

2. *Accretion disks*

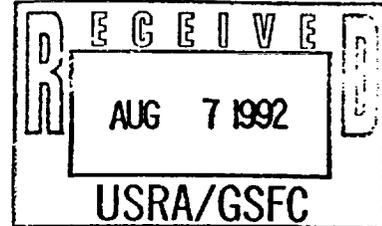
- I have continued in a collaboration with Dr. M. Plavec (UCLA) in modeling spectra of accretion disks in the Algol and W Serpentis classes of close binary systems.
- I have worked with Dr. A. Linnell (Michigan State University) on implementing my accretion disk program and the synthetic spectrum program SYNSPEC to his package of programs for calculating light curves of close binaries. The work still continues.
- I have worked with Dr. G. Rybicki (Harvard-Smithsonian CfA) on developing simple and useful models of accretion disks, based on the so-called multi-gray formalism. Results are expected to be published in the near future.
- I have started a collaboration with Dr. R. Wade (Penn State) on various aspects of theoretical modeling of accretion disks and interpreting observations of selected cataclysmic variables.

3. *Radiative transfer*

- I have continued to work with Dr. B. Lites (HAO, NCAR, Boulder) on developing a new computer program for including effects of partial redistribution to the multilevel, non-LTE line formation problems. The work still continues.
- I have been asked to write a chapter about "Solution of the radiative transfer problem" to the intended book "Numerical Astrophysics". The editors also ask all contributors to include a corresponding computer program, which will then serve as a benchmark computer program in the corresponding research fields for all other workers (similarly to "Numerical recipes" in numerical mathematics). I have already begun working on this project.

UNIVERSITIES SPACE RESEARCH ASSOCIATION
GODDARD VISITING SCIENTIST PROGRAM

EMPLOYEE SUMMARY OF ACCOMPLISHMENTS
(for the year ending 9/30/92)



Employee name: Gary Hinshaw

Task Number: 5000-821

General description of your research activities:

During the 1992 fiscal year my activities have been primarily devoted to support for the DMR experiment on COBE, I have also been spending part of my time analyzing some of the galactic data from the FIRAS experiment on COBE.

I spent a good deal of my time in the early part of the fiscal year working with the DMR team preparing the final drafts of 4 scientific papers which summarize the first positive detection of anisotropies in the Cosmic Microwave Background radiation. These papers were submitted to the Astrophysical Journal (3 Letters and 1 paper) on 1992 April 21, and were accepted on 1992 June 12. I am a co-author on all four of the papers. I was also one of five speakers from the DMR team to announce our results at the Spring meeting of the American Physical Society on April 23. Since the time of our announcement I have given several talks on our results, including a joint Physics and Astronomy Colloquium at Yale University.

The most important contribution I made to the analysis of the DMR data was to demonstrate, in collaboration with Chuck Bennett, that the signals seen in the DMR maps could not be attributed to galactic foreground emission. In addition to bolstering our confidence in a landmark cosmological result, we learned a great deal about the nature of galactic emission at microwave frequencies. For example, we learned that free-free emission from diffuse ionized hydrogen clouds are the dominant galactic signal in the frequency range from about 20 - 80 GHz, a result that was not entirely expected. In addition we learned that any significant abundance of cold dust must be distributed differently than the hot dust at high galactic latitudes.

My present work is focusing on further analysis of the COBE data, again mostly in collaboration with Chuck Bennett. The first project involves gathering a variety of extra-galactic source catalogues (eg. 5 GHz point sources, Abell clusters, x-ray surveys, and so forth) and cross-correlating them with the DMR sky maps to place more specific limits on the extra-galactic contribution to our maps. The second project is a study of the full FIRAS spectrum data with which we will attempt to map the galactic distribution of various emission line features seen in the data. This work has important ramifications for the large scale distribution of the ionized component of our Galaxy. The final project is to write a paper for the Review of Scientific Instruments which summarizes the performance of the DMR instruments in flight. The information in this paper will hopefully be of use to workers planning future long-term mission with radiometers in space.

In addition to the above projects I have been spending a reasonable portion of my time recently consulting some of the newer members of our team on programming and systematic error analysis. I suppose it is the teacher in me (left over from my days at Oberlin College) that enjoys this aspect of the job.

Describe any Significant Recognition of your work:

We announced the results from our first year of data at the Spring APS meeting on 23 April, 1992. Following the announcement, virtually every major newspaper in the world covered the story as front page news. Many of the stories carried quotes from prominent cosmologists, for example:

"What these people have found is what I would call the Holy Grail of modern cosmology", Micheal Turner, University of Chicago

"It is the discovery of the century, if not of all time", Stephen Hawking, University of Cambridge

While these quotes are no doubt exaggerations, it does give one an idea of the excitement generated within the community at the time of our announcement.

Our sky maps also appeared on the cover of the June 1992 issue of Physics Today, the main news periodical for the broader community of physicists.

Honors or Awards Received:

Biography included in Who's Who in Science and Engineering, 1992

Papers published or Accepted for Publication:

(Abstracts are appended to this document.)

"COBE Differential Microwave Radiometers (DMR): Calibration Techniques."

Astrophysical Journal, 391, 467, (1992)
C.L. Bennett, NASA Goddard Space Flight Center
G.F. Smoot, University of California, Berkeley
M. Janssen, Jet Propulsion Laboratory
S. Gulkis, Jet Propulsion Laboratory
A. Kogut, Universities Space Research Association
G. Hinshaw, Universities Space Research Association
C. Backus, Hughes/STX Corporation
M.G. Hauser, NASA Goddard Space Flight Center
J.C. Mather, NASA Goddard Space Flight Center
L. Rokke, Hughes/STX Corporation
L. Tenorio, University of California, Berkeley
R. Weiss, Massachusetts Institute of Technology
D.T. Wilkinson, Princeton University
E.L. Wright, University of California, Los Angeles
G. DeAmici, University of California, Berkeley
N.W. Boggess, NASA Goddard Space Flight Center
E.S. Cheng, NASA Goddard Space Flight Center
P.D. Jackson, Hughes/STX Corporation
P. Keegstra, Hughes/STX Corporation
T. Kelsall, NASA Goddard Space Flight Center
R. Kummerer, Hughes/STX Corporation
C. Lineweaver, University of California, Berkeley
S.H. Mosely, NASA Goddard Space Flight Center
T.L. Murdock, General Research Corporation
J. Santana, Hughes/STX Corporation
R.A. Shafer, NASA Goddard Space Flight Center
R.F. Silverberg, NASA Goddard Space Flight Center

"Structure in the COBE DMR First Year Maps."

Astrophysical Journal Letters (1992) (To appear 1 September 1992)

G.F. Smoot, University of California, Berkeley
C.L. Bennett, NASA Goddard Space Flight Center
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D.T. Wilkinson, Princeton University

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Astrophysical Journal Letters (1992) (To appear 1 September 1992)

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T.L. Murdock, General Research Corporation
R.A. Shafer, NASA Goddard Space Flight Center
R.F. Silverberg, NASA Goddard Space Flight Center
D.T. Wilkinson, Princeton University

"COBE Differential Microwave Radiometers (DMR): Preliminary Systematic Error Analysis."

Astrophysical Journal, TBD, (1992)

A. Kogut, Universities Space Research Association
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J.C. Mather, NASA Goddard Space Flight Center
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T.L. Murdock, General Research Corporation
R.A. Shafer, NASA Goddard Space Flight Center
R.F. Silverberg, NASA Goddard Space Flight Center
R. Weiss, Massachusetts Institute of Technology
D.T. Wilkinson, Princeton University

"COBE DMR Data Processing Techniques."

1st Ann. Astron. Data Anal. Conf., Tucson (1991)
P.D. Jackson, Hughes/STX Corporation
G.F. Smoot, University of California, Berkeley
C.L. Bennett, NASA Goddard Space Flight Center
J. Aymon, University of California, Berkeley
C. Backus, Hughes/STX Corporation
G. DeAmici, University of California, Berkeley
G. Hinshaw, Universities Space Research Association
P. Keegstra, Hughes/STX Corporation
A. Kogut, Universities Space Research Association
C. Lineweaver, University of California, Berkeley
L. Rokke, Hughes/STX Corporation
L. Tenorio, University of California, Berkeley

"Daily Quality Assurance Software for a Satellite Radiometer System."

1st Ann. Astron. Data Anal. Conf., Tucson (1991)
P. Keegstra, Hughes/STX Corporation
G.F. Smoot, University of California, Berkeley
C.L. Bennett, NASA Goddard Space Flight Center
J. Aymon, University of California, Berkeley
C. Backus, Hughes/STX Corporation
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C. Lineweaver, University of California, Berkeley
L. Rokke, Hughes/STX Corporation
J. Santana, Hughes/STX Corporation
L. Tenorio, University of California, Berkeley

Papers Submitted but not yet Accepted for Publication:

None

Papers Presented at Scientific Meetings:

Invited papers:

None

Contributed papers:

"COBE DMR Instrument Performance and Systematic Error Analysis."

Contributed Paper, Spring Meeting of the American Physical Society
23 April 1992

Colloquia, Seminars, and Special Lectures:

"COBE DMR Observations of Cosmic Microwave Background Anisotropies."

Special Seminar, Goddard Space Flight Center JOVE Retreat
23 July 1992

Joint Physics and Astronomy Colloquium, Yale University
7 May 1992

Special Seminar, Cosmology Data Analysis Center
6 May 1992

"COBE DMR First-Year Sky Maps."

Research Presentation to USRA Board of Trustees
23 April 1992

Community Service:

"COBE DMR Observations of Cosmic Microwave Background Anisotropies."
Invited Talk, Annual Meeting of the National Capital Astronomers
12 September 1992

University Collaborations:

The principle investigator for the DMR instrument, George Smoot, is a University of California employee. Thus I am collaborating on a daily basis with George and other members of his U.C. group in the course of analyzing the DMR data.

Other Collaborative Activities:

None

Supply any Additional Information you Feel Would be Useful in evaluating your performance:

None

"COBE Differential Microwave Radiometers (DMR):
Calibration Techniques."

ABSTRACT

The *COBE* spacecraft was launched 18 November 1989 U.T. carrying three scientific instruments into Earth orbit for studies of cosmology. One of these instruments, the Differential Microwave Radiometer (DMR), is designed to measure the large-angular-scale temperature anisotropy of the cosmic microwave background radiation at three frequencies (31.5, 53, and 90 GHz). In this paper we present three methods used to calibrate the DMR. First, the signal difference between beam-filling hot and cold targets observed on the ground provides a primary calibration that is transferred to space by noise sources internal to the instrument. Second, the Moon is used in flight as an external calibration source. Third, the signal arising from the Doppler effect due to the Earth's motion around the barycenter of the solar system is used as an external calibration source. Preliminary analysis of the external source calibration techniques confirms the accuracy of the currently more precise ground-based calibration. Assuming the noise source behavior did not change from the ground-based calibration to flight we derive a 0.1-0.4 % relative and 0.7-2.5 % absolute calibration uncertainty, depending on radiometer channel.

Subject headings: cosmic microwave background - instrumentation:detectors

"Structure in the COBE DMR First Year Maps"

ABSTRACT

We have analyzed the first year of data from the Differential Microwave Radiometers (DMR) on the Cosmic Background Explorer (COBE). We observe the dipole anisotropy, Galactic emission, instrument noise, and detect statistically significant ($> 7\sigma$) structure that is well-described as scale-invariant fluctuations with a Gaussian distribution. The major portion of the observed structure cannot be attributed to known systematic errors in the instrument, artifacts generated in the data processing or known Galactic emission. The structure is consistent with a thermal spectrum at 31, 53, and 90 GHz as expected for cosmic microwave background anisotropy.

We select the data with Galactic latitude $|b| > 20^\circ$ and remove the mean and dipole anisotropy. The rms sky variation, smoothed to a total 10° FWHM Gaussian, is $30 \pm 5 \mu\text{K}$. The rms quadrupole amplitude is $13 \pm 4 \mu\text{K}$. The angular auto-correlation of the signal in each radiometer channel and cross-correlation between channels are consistent and give an angular power-law spectrum with index $n = 1.1 \pm 0.5$, and an rms-quadrupole-normalized amplitude of $16 \pm 4 \mu\text{K}(\Delta T/T \approx 6 \times 10^{-6})$. These features are in accord with the Harrison-Zel'dovich (scale-invariant, $n = 1$) spectrum predicted by models of inflationary cosmology. The overall fluctuation amplitude is consistent with predictions by minimal theories of structure formation based on gravitational instability.

"Preliminary Separation of Galactic and Cosmic Microwave Emission for the COBE DMR."

ABSTRACT

The COBE Differential Microwave Radiometers (DMR) anisotropy experiment is sufficiently sensitive and free from systematic errors that our knowledge of Galactic emission is a limiting factor in interpreting the measurements of the 1-year DMR maps (Smoot et al. 1992). In this paper we construct preliminary models of microwave emission from our Galaxy based on COBE and other data for the purpose of distinguishing cosmic and Galactic signals. DMR maps, with the modeled Galactic emission removed, are fit for a quadrupole distribution. Our best estimate of the cosmic quadrupole is found to be $Q_{rms} = 13 \pm 4 \mu\text{K}$, $(\Delta T/T)_Q = (4.8 \pm 1.5) \times 10^{-6}$. Autocorrelation functions for individual Galactic components are presented. When Galactic emission is removed from the DMR data, the residual fluctuations are virtually unaffected and therefore they are not dominated by any known Galactic emission component.

Subject headings: cosmology - cosmic background radiation - Galaxies: Milky Way

Interpretation of the CMB Anisotropy Detected by the COBE DMR.

2

ABSTRACT

We compare the large scale cosmic background anisotropy detected by the *COBE* DMR instrument to the sensitive previous measurements on various angular scales, and to the predictions of a wide variety of models of structure formation driven by gravitational instability. The observed anisotropy is consistent with all previously measured upper limits and with a number of dynamical models of structure formation. For example, the data agree with an unbiased Cold Dark Matter (CDM) model with $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Delta M/M = 1$ in a 16 Mpc radius sphere. Other models, such as CDM plus massive neutrinos (Hot Dark Matter), or CDM with a non-zero cosmological constant are also consistent with the *COBE* detection, and can provide the extra power seen on 5-10,000 km s^{-1} scales.

Subject headings: cosmology – cosmic background radiation

"COBE Differential Microwave Radiometers (DMR):
Preliminary Systematic Error Analysis."

Abstract

The Differential Microwave Radiometers (DMR) instrument aboard the Cosmic Background Explorer (COBE) maps the full microwave sky in order to measure the large-angular-scale anisotropy of the cosmic microwave background radiation. Solar system foreground sources, instrumental effects, as well as data recovery and processing can combine to create statistically significant artifacts in the analyzed data. We discuss the techniques available for the identification and subtraction of these effects from the DMR data and present preliminary limits on their magnitude in the DMR one-year maps (Smoot et al. 1992). The largest effect is the instrument response to the Earth's magnetic field, which contributes up to $375 \mu\text{K}$ to the raw data in the worst channel. Emission from the Earth is weak (less than $47 \mu\text{K}$ in the raw data at 95% confidence). Residual uncertainties in the best DMR sky maps, after correcting the raw data for systematic effects, are less than $6 \mu\text{K}$ for the pixel rms variation, less than $3 \mu\text{K}$ for the rms quadrupole amplitude of a spherical harmonic expansion, and less than $30 \mu\text{K}^2$ for the correlation function (all limits 95% confidence level). These limits are a factor of 5—40 lower than the level of anisotropy in the microwave background detected in the one-year DMR sky maps: $30 \pm 5 \mu\text{K}$ rms, $13 \pm 4 \mu\text{K}$ quadrupole, and $1194 \pm 499 \mu\text{K}^2$ for the correlation function (Smoot et al. 1992, Bennett et al. 1992b, Wright et al. 1992).

Subject headings: cosmic background radiation